RECENT CONTRIBUTIONS ON THE EFFECT OF LOCAL DAMAGES ON THE BEHAVIOR OF CIRCULAR STEEL HOLLOW SECTIONS

Tohid Ghanbari Ghazijahani *, Hui Jiao and Damien Holloway

School of Engineering & ICT, University of Tasmania, Hobart, Australia;

**Corresponding Author, Phone: (+61) (0)469 311 896,*

E-mail: tohid.ghanbari@utas.edu.au, tohidghanbari@gmail.com

ABSTRACT

Despite many papers on the structural response of thin circular sections, the effect of large imperfections – largely imposed due to damage, collisions, etc. – still leaves many open questions. Over the past few years however, there has been a significant body of tests on steel members with large imperfections, conducted by the authors at the *University of Tasmania,* with a particular focus on circular hollow sections under different loading conditions. The effect of geometrical irregularities of such structures was examined and subsequently presented in several papers. This paper incorporates these new advances into an organized summary, including key findings of the mentioned experimental data on the effect of local damages on the capacity of different structures with various geometrical features. Discussions are presented on the topic and some general recommendations made in relation to real structures in practice.

KEYWORDS

Steel, thin shells/tubes, damage, dent imperfection.

INTRODUCTION

Numerous papers have investigated the effect of different types of imperfections on steel structures. Prabu et al. studied buckling of dented steel cylindrical shells under axial compression (Prabu, Raviprakash et al. 2010), showing an adverse effect of the dent imperfection. Gavrilenko and V. L. Krasovskii studied the effect of a single local dent on steel cylindrical shells (Gavrilenko and Krasovskii 2004). The proposed method in this study was found to be effective to estimate the capacity of the dented structures within a specific range of the geometry. Furthermore, Karroum et al. studied indentation of thin cylinders in which wedge-shaped indenters were employed (Karroum, Reid et al. 2007). FE and experimental methodologies were conducted to identify the failure. Paik studied the residual stress of dented elements (Paik 2014), in which FE computations and test observations were thoroughly discussed on the models.

Lately, 27 specimens were tested by the authors where the buckling behavior of thin cylindrical shells was evaluated under compression (Ghanbari Ghazijahani, Jiao et al. 2014). The capacity decrease of such structures was also set forth in this research. The authors examined the bending capacity of damaged CHS tubes (Ghanbari Ghazijahani, Jiao et al. 2015), wherein the effect of dent imperfection was thoroughly studied. Further studies investigating dented shell structures subject to pressure can be seen in Refs. (Ghanbari Ghazijahani and Showkati 2013, Rathinam and Prabu 2013, Ghanbari Ghazijahani, Jiao et al. 2014), in which the capacity reduction was obtained for the imperfect models. Plastic buckling of locally damaged steel tubes was investigated by the authors (Ghanbari Ghazijahani, Jiao et al. 2015). The effect of the damage imperfections and the results of this study will be discussed in detail in the coming sections.

Fabrication type imperfections mostly under axial compression are found in numerous paper, e.g. (Hutchinson, Muggeridge et al. 1971, Brush and Almroth 1975, Calladine 1989, Deml and Wunderlich 1997, Holst, Rotter et al. 1999, Holst 2011, Ghanbari Ghazijahani and Showkati 2012, Ghanbari Ghazijahani and Showkati 2013) in which the capacity and failure modes of different structures were expounded upon. Two innovative methods were proposed to investigate imperfect shells (Gavrilenko 2003), wherein even a single dent was found to strongly affect the buckling load. Hambly and Calladine (Hambly and Calladine 1996) experimentally investigated damaged cylindrical shells subject to axial compression. The detrimental effect of the dent imperfection in nearly perfect specimens was obtained in this research.

This paper aims to incorporate the results of the recent experimental studies on the effect of locally damaged steel circular hollow sections into organized discussions and recommendations. The discussions will lead to useful tips on the adverse effects of the dent in the mentioned studies, which can be significantly employed in practice. Figure 1 illustrates a schematic view of the dent imperfection and the specimens.

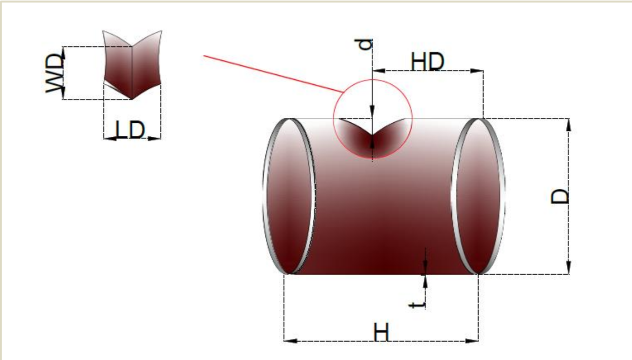


Figure 1 Typical schematic view of the dent imperfection.

LARGE IMPERFECTIONS AND PLASTIC BUCKLING UNDER COMPRESSION

Description of experiments

Steel circular hollow tubes with a moderate ratio of diameter to thickness of 47.6 were studies experimentally (Ghanbari Ghazijahani, Jiao et al. 2015). Indentation was conducted using an *Avery Universal Testing Machine* and a V-shape indenter. Dent imperfections with different geometries, inclinations and distances from the end edges were adopted in this study. Full descriptions about the experimentation can be found in (Ghanbari Ghazijahani, Jiao et al. 2015).

Failure mode and capacity

The tubes were thick enough to behave plastically, i.e. the yield governed the failure for these specimens (Ghanbari Ghazijahani, Jiao et al. 2015).The failure mode for the dented specimens was similar to the undented reference specimens, wherein the side of the tubes opposite the dents buckled in an elephant foot mode. As well, failure was accompanied by the enlargement of the dented zone and geometrical development of the deformations to the areas of the vicinity of the dents. Overall, the deformations were concentrated in the end areas of the tubes and the dented zone itself (Figure 2).

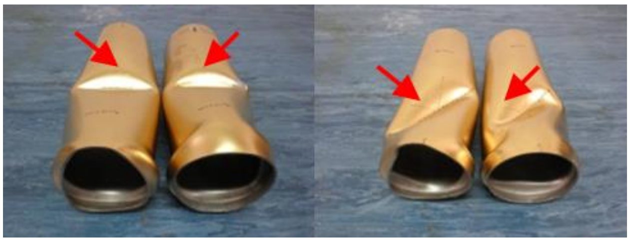


Figure 2 Failure mode of the tube specimens with different dent shapes under compression.

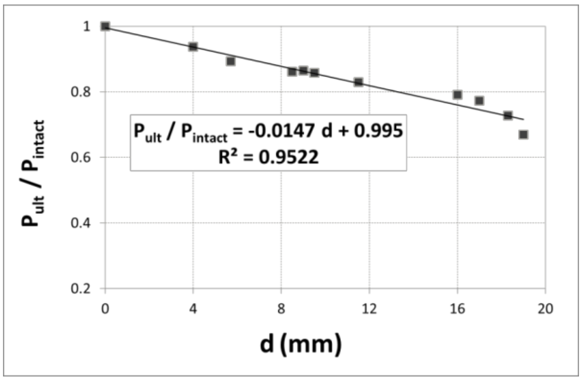


Figure 3 Capacity ratio of the dented to the intact tubes under compression.

In this study the ultimate axial load (P_{ult}) was obtained for each specimen when the peak load was reached after a nonlinear plastic load displacement trend. Figure 3 shows the capacity ratios of the dented to intact tubes for different specimens, which was plotted against the depth of the dent (*d*). As observed from the graph, a moderate decreasing effect of the dent imperfection is plainly seen, where the more the depth of the dent the more the reduction of the ultimate axial capacity. The location of the dents and the orientation turned out to be of a lesser significance.

SLENDER CIRCULAR HOLLOW SECTION AND THE IMPOSED DAMAGES AGAINST COMPRESSION

Thin shell specimens and experimental method

Very thin specimens were investigated by the authors in which the dent shape damage were exerted to the body of the shells (Ghanbari Ghazijahani, Jiao et al. 2014). The indentation was performed by a round edge indenter. The creation of the dents was followed by applying the controlled compression over the surface of the shells. The diameter to the thickness ratio (D/t) was different for the specimens so that the specimens were categorized into two groups: (i) D/t = 604, and (ii) D/t = 340. Thus, the slenderness of the first group was two times more than the second category.

Failure mode and Impact of the dent on the capacity

The failure predominantly formed as a diamond mode – a typical buckling form for slender shells – which was seen both for intact and dented specimens. Figure 4 shows typical failure modes for the specimens under axial compression. Note that the area around the top edge was the most susceptible zone to buckling. For some of the dented specimens the failure was initiated from the dented area or end area or concurrently. The bifurcation type of failure was observed, wherein the second bifurcation point was detected after the first drop of load was seen in the load displacement curves (Ghanbari Ghazijahani, Jiao et al. 2014). It is fitting to mention that the same failure was observed for both groups with different geometries.

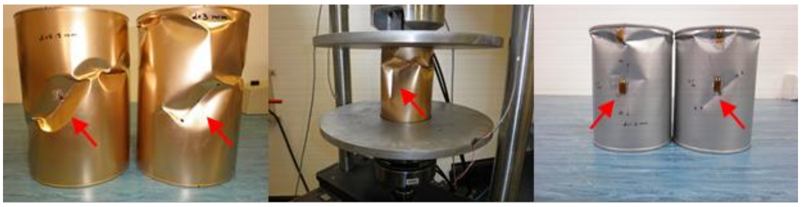
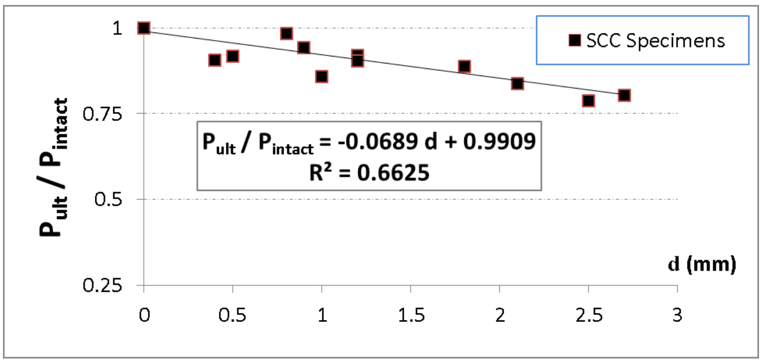


Figure 4 Specimens under compression with different dent imperfections after failure

Figure 4 shows the impact of local damages on the capacity of the mentioned thin specimens. The effect of the damage for SCC specimens (D/t = 604) was greater than their less slender counterparts indicating that the dent seems more detrimental for the slenderer specimens against axial compression. Although this conclusion may not necessarily be simply extrapolated to a wide range of geometries, sufficient experimental data is still required to draw definitive conclusions.



(a)

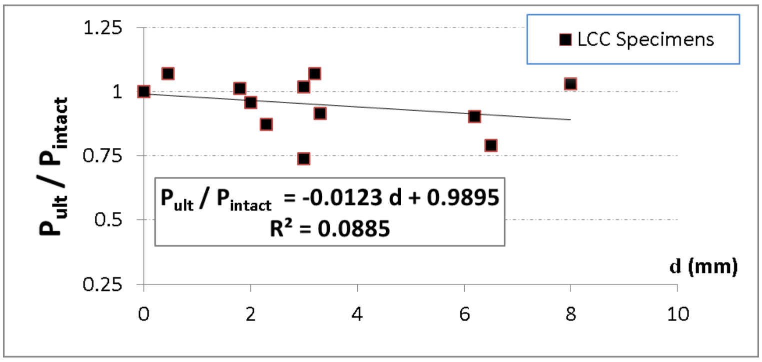
(b) 

Figure 5 Capacity ratio of dented to intact thin shells under compression: (a) SCC specimens (*D*/t = 604) and (b) LCC specimens (*D*/t = 340).

EXTERNALLY PRESSURIZED DENTED THIN CIRCULAR SHELLS

Geometry of specimens and experimental method

The same specimens as described for the previous section were employed for this program. The method of indentation was also the same as the dented specimens under compression, which were discussed earlier. The boundary conditions were simply supported which was conducted through the circular grooves machined at the end plates. Dented thin circular shells of revolution were used while they were subjected to the peripheral pressure (Ghanbari Ghazijahani, Jiao et al. 2014).

Failure modes and influence of the dent shape irregularities on the buckling load

The sensitivity of these structures to the local large imperfections – capacity wise and buckling mode wise – was assessed in this study. As can be found in the mentioned reference, the failure mode was initiated from the areas adjacent to the dent imperfection especially for the larger dents, whereas for the smallest dents the occurrence of the initial lobe of the buckling may or may not be affected by the dent. This is attributed to the fact that the dominance of the fabrication related imperfections could affect the onset of buckling. Thus we hypothesize that there is an interaction between the normal fabrication-related imperfections and the smaller dents. Indeed, the distribution and/or the amplitude of the normal imperfections can critically affect the initiation of buckling, which can definitely correlate with the depth and the width of the damages.

When it comes to the larger dents, different inclinations of the dents affected the buckling mode. As an instance, a large longitudinal dent can lead the yield lines to form nearby the dented area. It is worth mentioning that the overall buckling in the dented specimens, i.e. complete formation of several lobes around the circumference, took place by the same mechanism as the undented specimens.

Figure 7 shows the decreasing trend of the capacity (critical buckling load) as the depth of the dent increases. A moderate effect of the dent imperfection is seen through the figure. Given the capacity reduction of the equivalent specimens under compression discussed in the last section, the specimens under external pressure behaved structurally steadier when they were exposed to the external pressure. This response can be attributable to the geometry of a typical dent against external pressure and axial compression, i.e. the direction of the stresses for both load cases relative to the dent imperfection can suggest this capacity differences.

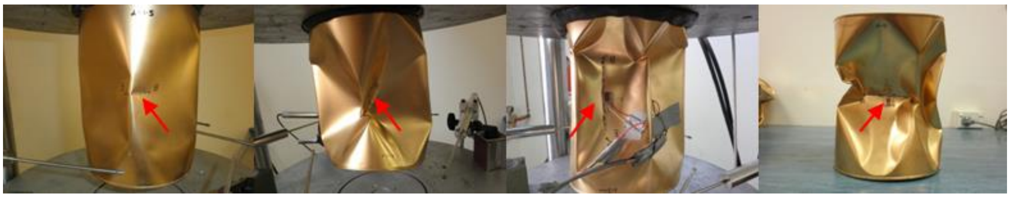


Figure 6 Specimens under external pressure with different dent imperfections after failure.

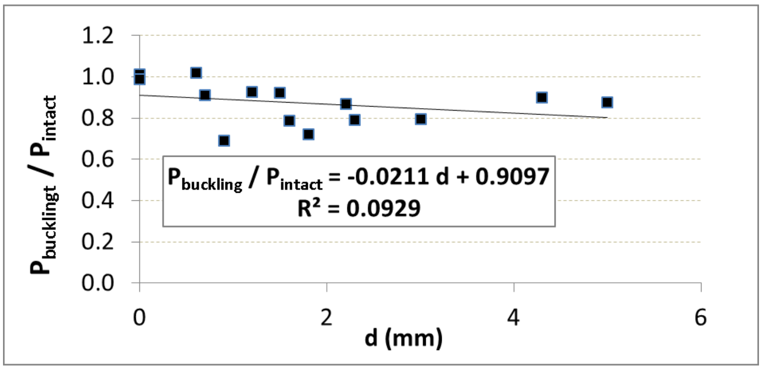


Figure 7 Capacity ratio of dented to intact thin shells under external pressure

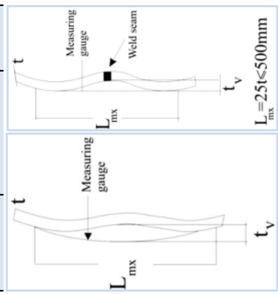
COMPARISONS AND DISCUSSIONS

The decreasing trend for the specimens with plastic buckling under axial load was in large part, linear. Less scatter of the data was seen as the regression value indicated a magnitude very close to the unity (Figure 3). This demonstrates a steadier response of the thicker circular hollow sections in which the yield phenomenon prevails rather than the local instabilities in the pre-yielding zone.

It is quite evident that the scatter of the data for the thinner specimens subjected to the axial compression was far more sizable than the thicker tubes presented before (Figure 5). This definitely implies more certainties in the response of the thicker specimens as pre-yielding local instabilities were not prevalent in thicker tubes.

Comparing the specimens under external pressure with equivalent specimens under compression, the scatter of the data for the specimens under external pressure was higher, which suggests more certainty of the response of the dented specimens under axial compression than external pressure.

ESSCRec, 2008	L=Ir:t_r=W t_r<1% of L_{mx}
ENV 1993-1-6, 2007	L_{mx}=L_g:t_r=Δw_0 $t_r \leq 0.006L_{mx}$ OR (0.01 L_{mx}, 0.016 L_{mx} for different classes)
DIN 18800-4	t_r<1% of L_{mx}



(a)

(b)

Figure 8 Recommended tolerances for the imperfections by three different codes, also available in: (Fatemi, Showkati et al. 2013).

Quite a few codes tolerated allowable values for the ordinary fabrication imperfections as provided in ESSC (2008), ENV (1993) and DIN 18800 (1990). It is reiterated that the results of the mentioned experiments in this paper necessitate further evaluations in the future updates of the mentioned codes to include the large local imperfections in the design codes. This is proposed thanks to the fact that in some cases the effect of large imperfections is not as large as they would be imagined.

CONCLUSIONS

The effect of large imperfections caused by damage or physical collisions in the service life of the thin-walled circular hollow sections was investigated in this study. Experimental data were evaluated to organize the experimental findings on the mentioned structures under axial load and external pressure. The findings were incorporated into a set of organized results to present and compare the effect of dent imperfections in different applications. Comparisons demonstrated that the effect of the dent imperfection was greater for the specimens under axial loading compared to the cases subject to the external pressure. It is believed that the results of this study fairly necessitate reconsideration of the present available codes to include the effect of imperfection in order that the available tolerances are updated. This is indeed due to the fact that in some cases the dents beyond the tolerated magnitudes may still have some little effects on the capacity of different structures.

REFERENCES

DIN 18800. Stahlbauten.Teil 4: Stabilitätsfalle,Schalenbeulen 1990".

ECCS EDR5. European Recommendations for steel construction. Buckling of shells, 5th ed. In: Rotter JM, Schmidt H, editors. European convention for constructional steelwork. Brussels; 2008384pp.

EN1993-1-6: Eurocode 3Design of steel structures, Part 1.6: General rules—Strength and stability of shell structures. Eurocode 3 Part 1.6, CEN, Brussels. 2007.

"Ghanbari Ghazijahani T, Jiao H, Holloway H, Experiments on Dented Steel Tubes under Bending, Journal of Advances in Structural Engineering (accepted in press)."

Brush, D. O. and B. O. Almroth (1975). Buckling of bars, plates, and shells, McGraw-Hill New York.

Calladine, C. R. (1989). Theory of shell structures, Cambridge University Press.

Deml, M. and W. Wunderlich (1997). "Direct evaluation of the 'worst'imperfection shape in shell buckling." Computer methods in applied mechanics and engineering 149(1): 201-222.

Fatemi, S. M., H. Showkati and M. Maali (2013). "Experiments on imperfect cylindrical shells under uniform external pressure." Thin-Walled Structures 65: 14-25.

Gavrilenko, G. (2003). "Numerical and analytical approaches to the stability analysis of imperfect shells." International applied mechanics 39(9): 1029-1045.

Gavrilenko, G. and V. Krasovskii (2004). "Stability of circular cylindrical shells with a single local dent." Strength of materials 36(3): 260-268.

Ghanbari Ghazijahani, T., H. Jiao and D. Holloway (2014). "Experimental study on damaged cylindrical shells under compression." Thin-Walled Structures 80: 13-21.

Ghanbari Ghazijahani, T., H. Jiao and D. Holloway (2014). "Experiments on dented cylindrical shells under peripheral pressure." Thin-Walled Structures 84: 50-58.

Ghanbari Ghazijahani, T., H. Jiao and D. Holloway (2015). "Fatigue tests of damaged tubes under flexural loading." Steel and Composite Structures 19(1): 223-236.

Ghanbari Ghazijahani, T., H. Jiao and D. Holloway (2015). "Plastic buckling of dented steel circular tubes under axial compression: An experimental study." Thin-Walled Structures 92: 48-54.

Ghanbari Ghazijahani, T. and H. Showkati (2012). Bending Experiments on Thin Cylindrical Shells. Materials with Complex Behaviour II, Springer: 119-139.

Ghanbari Ghazijahani, T. and H. Showkati (2013). "Experiments on cylindrical shells under pure bending and external pressure." Journal of Constructional Steel Research 88: 109-122.

Ghanbari Ghazijahani, T. and H. Showkati (2013). "Locally imperfect conical shells under uniform external pressure." Strength of Materials 45(3): 369-377.

Hambly, E. and C. R. Calladine (1996). "Buckling experiments on damaged cylindrical shells." International journal of solids and structures 33(24): 3539-3548.

Holst, J. (2011). "Local dimpling of the shell surface of a tank due to shrinkage effects." Structures and Granular Solids: 153.

Holst, J. M. F., J. M. Rotter and C. R. Calladine (1999). "Imperfections in cylindrical shells resulting from fabrication misfits." Journal of engineering mechanics 125(4): 410-418.

Hutchinson, J., D. Muggeridge and R. Tennyson (1971). "Effect of a local axisymmetric imperfection on the buckling behaviorof a circular cylindrical shell under axial compression." AIAA Journal 9(1): 48-52.

Karroum, C., S. Reid and S. Li (2007). "Indentation of ring-stiffened cylinders by wedge-shaped indenters—Part 1: An experimental and finite element investigation." International journal of mechanical sciences 49(1): 13-38.

Paik, J. (2014). "Dented structures and residual strength." Condition Assessment of Aged Structures: 231.

Prabu, B., A. Raviprakash and A. Venkatraman (2010). "Parametric study on buckling behaviour of dented short carbon steel cylindrical shell subjected to uniform axial compression." Thin-Walled Structures 48(8): 639-649.

Rathinam, N. and B. Prabu (2013). "Static buckling analysis of thin cylindrical shell with centrally located dent under uniform lateral pressure." International Journal of Steel Structures 13(3): 509-518.